5   # A Multi-Agent System for Automated Image Analysis and Understanding

Background of the Invention

The present invention relates to the field of image analysis and more specifically to methods for automated image segmentation, analysis and understanding by means of

10   a novel Multi-Agent system.

There currently exists a broad spectrum of image analysis technologies and methods that try to provide automated image analysis. However, major problems arise from these methods as they are most commonly based on simple spectral thresholding techniques or variations thereof. There have been many attempts at providing efficient

15   automated image analysis methods, some of which have been more or less successful, such as multiscale analysis and deformable models. In recent attempts, there have been many developments in methods that combine already existing techniques. However, the main problem with the combination of existing methods consists in determining the optimal set of parameters and order in which the methods should be

20   applied. With the recently added requirement of symbolic image interpretation in the industry as well as in academia, in addition to image segmentation, standard image analysis methods have even more shown to be inadequate. To efficiently address these issues, a new theoretical field known as Multi-Agent systems has been adopted and formalized by the inventors specifically for the problems at hand. Although the

25   basic concepts in Multi-Agent systems are known in the art, the present invention brings forth completely novel methods therein for allowing robust and fully automated image segmentation, analysis and understanding.

Patent 5,978,520 provides a method and system for interactively generating vector data, more specifically to draw vector lines, from drawing data by means of a basic

30   multi-agent system. The provided multi-agent system is based on the concept of a supervisor agent that enforces actions upon the agents it controls when problems or contradiction arise. In contrast to the invention described in 5,978,520, the present invention provides an automated system and methods for the automatic extraction and quantification of objects in images as well as symbolic image interpretation by means

35   of a multi-agent system composed of fully autonomous agents.

5   ## Summary of the Invention

An object of the present invention is to provide an image analysis and segmentation method and apparatus thereof for performing automated image analysis in various fields of applications where extraction and quantification of objects in images is required and where precise and robust analyses are of primary importance.

10   Another object of the present invention is to provide a multi-agent system that integrates novel concepts in order to achieve full automation and maximum precision in image analysis contexts where complex image structures are required to be analyzed. *The herein described invention therefore provides a multi-agent system that integrates the concepts of multiscale-based agent cooperation and sensing, sub-*
15   *primitive agent specializations, dynamic agent parameterization as well as incremental feedback.*

Overall there is provided methods and apparatus for first inputting digital images, then automatically analyzing the digital images by means of a specialized and autonomous multi-agent system that is initialized and assigned to the considered
20   images by a program, and finally for displaying to the user and for saving in repositories the results generated by the multi-agent system.

Brief Description of the Drawings

The invention will be described in conjunction with certain drawings which are for the purpose of illustrating the preferred and alternate embodiments of the invention
25   only, and not for the purpose of limiting the same, and wherein:

Figure 1 displays the basic agent initialization and assignment process.

Figure 2 depicts the various agent components for an embodiment.

Figure 3 displays the basic flow of an example agent initialization and assignment process for one embodiment.

30   **Figure 4** displays the entire system's basic operational flow.

Figure 5 depicts the concept of an agent sensing an image by means of its sensors.

5   **Figure 6** depicts the basic steps involved in the agent-to-agent communication process by means of the Receiver/Transmitter component.

Figure 7 depicts the concept of multiscale agent specialization and cooperation.

Figure 8 is a representation of the components involved in providing multiscale sensors.

10   **Figures 9a - 9b** represent the concept of multiresolution image sensing.

Figures 10a – 10c depict the process of multiscale information gathering by an agent.

Figure 11 is a drawing of a typical satellite image landscape.

Figure 12a – 12b illustrates the extraction of water course ridges and the process of agent initialization on these ridges.

15   **Figure 13** illustrates the initialization of Border Agents and the path following by Ridge Agents.

Figure 14a – 14b illustrate the bridge detection process.

Figure 15a – 15b represents the semantic interpretation of water courses.

Figure 16a – 16b illustrate the detection of entities within water courses.

20   **Figure 17** illustrates a basic configuration of an apparatus for analyzing images comprising N processing nodes.

Referring numerals comprised in the figures are here forth mentioned in the detailed description within brackets such as: (2).

Detailed Description

25   Although it is not the objective of the present invention to extensively describe hardware infrastructures that may be more optimal than standard personal computers as support to the herein described multi-agent system, we however describe a distributed hardware configuration that may be used in the present context.

5   Distributed Systems

A multi-agent system is inherently highly distributable; from the fact that individual or a group of agents can reside on separate machines and communicate with one another over a network connection. From this, various types of distributed architectures can be considered in the implementation of a multi-agent system.

10   Considering applications such as high resolution satellite image analysis, where considerable processing power is required to process the data in reasonable time frame, a distributed hardware platform may be required. A typical configuration is that of two or more networked computers where each computer (node) processes information using a program, and where a program communicates with another

15   program residing on another computer through a communication interface. Patent 6,350,239 discloses a basic distributed software architecture for medical diagnostic systems, where distinct modules that perform well defined and separate functions are executed on separate computers. The invention disclosed in 6,350,239 does not however address the challenging problem of distributing a single "module" over a

20   plurality of nodes. Contrastingly, the herein described invention provides means for distributing a single "module" over a plurality of computers or processing nodes, where each node may be host to one or a plurality of software agents that each perform a subtask of the global task (module). Through communication and scheduling of events, the plurality of software agents will achieve the required end-

25   result. An example multi-node apparatus is illustrated in Figure 17. Depending on the nature of the application, the distributed system can be either loosely or tightly coupled. In the former case, the system can be a cluster-based backbone, where each processing node is physically located near one another, in a rack mounted configuration for instance, and where each node is networked to a neighboring node

30   using a high-speed network interface and cable (such as 1Gb fiber-optics interconnects). The use of high speed networking reduces the communication latency between any program and module required to exchange information. In the loosely coupled scenario, the backbone may comprise networked computers physically remote to one another between which information can be exchanged using a

35   networking protocol such as TCP/IP.

5   Although the present invention is detailed with an embodiment using a single personal computer as computational backbone, it is understood that it can be extended to a more sophisticated architecture such as a cluster system.

Entire System

The entire system comprises two main segments: A first segment that integrates basic
10   hardware and software components that form the basic backbone on which the multi-agent system relates, and a second segment that is the multi-agent system itself which comprises a plurality of software agents and basic software components.

Referring to Figure 1, the first process involved in the system consists in inputting one or a plurality of images by means of an input device (2). The latter can be a standard
15   input/output device for reading digital data from a repository, or from an imaging device, and can comprise a communication interface to read the data from remote repositories over a network such as the Internet. Once the image(s) read by the device and stored in memory, the Multi-Agent initialization and assignment program is instantiated. The program instantiates one or a plurality of software agents and makes
20   these software agent instances accessible in memory (4). Once the agents are instantiated, the program assigns the agents to the images that are required to be analyzed (8). In one embodiment, once the agents have been instantiated, they become entirely autonomous entities, making their own decisions and acting according to their goals and states (6). In one embodiment, the agents can be
25   randomly assigned to the images, wherein the program positions each of the agents at a random coordinate within the image. In another embodiment, the agents are strategically positioned within the image according to *a priori* knowledge on the problem at hand and general image structures, as well as according to the agent's specialization. In an example embodiment, the initialization and assignment program
30   invokes a pre-processing method for detecting local minima within the image as initial landmarks for positioning the agents. Referring to Figure 3, this initialization process consists in first detecting the minima within the image using the said pre-processing method (24). For each of the said detected minima, spatial coordinates are extracted by means of the said method, wherein the said coordinates serve as the
35   initial positioning coordinates, and are saved in memory (26). The initiation and assignment program is then input the set of coordinates, for which it automatically

5   assigns the initial agents by instantiating each of the agents and registering the latter
     with their according pixel coordinate and value (28). From this point, the assigned
     agents will be autonomous and can move within the image to inspect other image
     regions and associated image pixels.

     Referring to Figure 4, the entire system's overall operational flow comprises four
10   main steps: first inputting a digital image to the system (30), then initiating the Multi-
     Agent system (32), followed by the actual step of image analysis by means of the
     Multi-Agent system (34), and finally, displaying the segmented image and associated
     results (36).

     ## Multi-Agent System

15   The current invention relates to a novel multi-agent system devised for the automated
     analysis and segmentation of digital images.

     ## Agent Architecture
     By definition a multi-agent system comprises a plurality of agents. The present multi-
     agent system comprises a plurality of complex agents that have the means to receive
20   information, take decisions, communicate, and take action, in an autonomous manner.
     To achieve this, a specific agent architecture that comprises a plurality of components
     has been devised. In one embodiment the components are the following:
          - Sensor(s)
          - Processor(s)
25   - Actuator(s)
          - Receiver/Transmitter
          - Neural Processor(s)
          - State machine (s)
          - Memory unit(s)

30   These components provide all the necessary means for creating autonomous and
     minimally "intelligent" agents. Each of these agents operates by first receiving stimuli
     from the external environment. Referring to Figure 2, an agent first receives input
     from either its sensor component (10) or its receiver/transmitter component (16). The
     sensors provide the agent with means for sensing its physical environment, which is in
35   the present invention one or a plurality of digital images. In this sense, the sensors
     provide the agent with a view of the digital image, wherein the said view is composed
     of processed or unprocessed pixel values that are within the range of the agent's

5   sensors within the image. Referring to Figure 5, in one embodiment the agent has two circular sensors (38) that are positioned according to the agent's position within the image, as depicted by (40) which refers to an image region. Image objects are indicated by (42). When the agent senses the image using its sensors, it has an appreciation of the image content based on the pixel values, from 0 to 255 for

10   instance, comprised within its sensors. Again in Figure 5, the agent's sensors overlay portions of image objects that may have different pixel values (44 and 46). At this point, the agent receives image information from its sensors that indicates it is on image objects.

As opposed to receiving image information by means of sensors, the agent's

15   Receiver/Transmitter component provides means for the agent to communicate with other agents and therefore receive and/or transmit valuable information. This communication can be for instance with objective of negotiating, collaborating, or perhaps simply update some information or knowledge cumulated by the entire multi-agent system. In one embodiment, when an agent initiates communication with

20   another agent, the said agent (48) first queries an Agent Registry (50) that holds a list of agents that are instantiated in the system along with their associated key or ID (52). The agent then uses the key or ID to open a communication channel with the other agent (54). Finally, once the communication channel with the other agent is established, the agents are free to communicate (56). In another embodiment, the

25   Receiver/Transmitter component is used to send information to or receive from a shared memory, where information can be gathered and accessed by all agents. This shared memory can be a database or a specific data structure residing in memory and made available to all agents.

Once external stimuli are input by the agent, the following steps involve multiple

30   components and require the agent to take action, and may also require the agent to make a decision before taking action. Referring to Figure 2, the information input by the sensors (10) is channeled to both or either the Neural Processor (18) and Processor (12) components. On one hand, the Processor performs various type of processing operations on the input information, such as, without limitation, edge detection, contrast enhancement or computation of statistics. On the other hand, the Neural

35   Processor component can perform classification tasks on the raw input information or

5   on information processed by the Processor. In one embodiment, the Neural Processor identifies whether the input information is the edge of an object in the image. In general, the Neural Processor can identify the information input to it by means of classification or can incrementally generate a new knowledge base in conjunction with the Memory Unit (22). This incremental aspect of the Neural Processor provides

10   the agent with means for learning on its own and can therefore adapt itself to new problems and new types of images. This can be achieved by first inputting the sensor information in the Neural Processor, then automatically classifying the input information and saving a descriptor of this information along with its associated class in the Memory Unit. In one embodiment, the Neural Processor is comprised of one or

15   a plurality of Artificial Neural Networks, in which case the learning process further adapts the Networks' weights. In another embodiment, the Neural Processor comprises Self Organizing Networks such as Self Organizing Maps, Growing Cell Structures, or any variants thereof. The self organizing networks can provide powerful means for automatically classifying and characterizing the visual information input by

20   the agent's sensors.

     An agent further comprises an Actuator component (14) and can also comprise a State Machine (20). On one hand, the Actuator is the component that controls the agent's process of taking action. It is a general component and can control the process of communicating, proper information dispatching, adapting sensors, or even the process

25   of moving in the image and changing its content. Specific behavior or decision making can be achieved in conjunction with the State Machine which serves as the Agent's pre-defined mental states. In one embodiment, the agent's Actuator will force the adaptation of the Agent's sensors based on the output of the Processor, State Machine, Neural Processor, or any combination thereof. The sensor adaptation can

30   comprise, without limitation, changing the size of the sensors so as to view more or less information at one instant within the image. Another adaptation can be to enforce the sensors to view the information at a specific scale within a multiscale view of the image. In another embodiment, the Agent will move in a specific direction in the image according to the Actuator's command based on the knowledge acquired by the

35   other components. This process of moving an agent in the image can take the form: move to coordinate (x,y) and sense image using sensors at these new coordinates. In which case, the Agent autonomously moves in the image. As the agents' general

5   objectives are to analyze and segment images, the Actuator component is also
     responsible for the action of changing pixels within an image, as part of the image
     segmentation process. When an agent is in the mental state of "segmentation", as
     defined by its State Machine component (see below), the agent changes the value of
     the pixel on which it finds itself. The change in value can be of binary form (change

10   any pixel to a 1 or a 0), or can also be of any other value. Each agent specialization
     may change the pixel values to their own predefined value, which results in
     associating these specific pixels to their own class. For instance, a water agent can
     change the values of pixels it identifies as "water" to a unique value of 255, where
     pixels segmented by other specialized agents will have values different than 255. In

15   the present invention, the original input images are never directly modified, but
     instead copies of the images are created and used by the system. In such case, the
     segmented image that comprises modified pixel values will be done on a copied
     image, used by every agent in the system.

     The agent's State Machine component provides means for pre-programming desired

20   behaviors and patterns upon the activation of a specific state. For any given state the
     agent is in, if this particular state is coded in the State Machine component, then an
     action or a sequence of actions that is to be taken is directly determined from this
     component. Upon definition of an action or set of actions, the State Machine will
     work in conjunction with the Actuator for the agent to execute the required actions. In

25   specific embodiments the State Machine component is defined by Decision Trees and
     Finite State Machines. An example sub-sequence from the State Machine component
     could be as follows:

     | ...

     | *IF sensor input information not classified by Neural Processor*

30 | *Adapt sensors*
          | *Revalidate input*
     | ...

     The sub-sequence above provides a simple view of how the component can be
     involved in the execution of actions when the agent is in a specific state. In this

35   particular example, the agent's Neural Processor was not able to identify the nature of
     the information input by the sensors and therefore finds itself in an "Information not
     Classified" mental state. This state is encoded by the State Machine and defines the

5   various actions required to be taken by the agent when such a state is encountered. The example sub-sequence is with respect to the dynamic adaptation of the sensors, where when the information is not classified, the agent is required to change its sensors' configuration (adapt) and revalidate the information input by the later. In one embodiment, when the agent cannot readily identify the information as being part of

10   an image object's edge, the sensors dynamically change the scale and resolution at which the information is considered, a method that may facilitate the identification process. Although the Example State Machine sub-sequence is of simple nature, it is understood that the complete decision tree or finite state machine may comprise a broad range of states and decision processes. Although not directly illustrated in

15   Figure 2, the Receiver/Transmitter component may also be controlled in conjunction with the State Machine, where for instance a simple incoming communication may trigger a predefined sequence of actions as defined by the component.

According to the herein described Agent Architecture, the present Multi-Agent system can be composed of specialized agents that make decisions and take actions

20   specifically according to their specialization and in accordance with the inherent collaborative aspect of the system. From the previous description of the basic components that compose an agent, it is clear that an agent can integrate derived components (same components with modifications) as well as a plurality of other components. In one embodiment, each agent specialization has sensors that can differ

25   in shape, sensitivity, specificity and behavior. For instance, an agent that is specialized for the detection of object contours can have Neural Processor and Sensors that are specialized for the detection of edges. In another embodiment, an agent can be specialized for the analysis of high noise images, where the agent will be adapted to perceive the images as a multiscale representation so as to be robust to the

30   noise and artifacts. A plurality of agent specializations can be readily devised with the herein described agent architecture. It is therefore understood that the Invention is not limited to the above described embodiments of agent specialization.

Multiscale Perception

Based on the beforehand described agent architecture, an aspect of the present system

35   is the multiscale-based agent cooperation and image perception. The concept of multiscale perception herein considered comprises two main aspects: 1) multiscale

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5   perception achieved through the cooperation of agents specialized for distinct or
     multiple scale levels, and 2) multiscale perception achieved by means of multiscale
     and multiresolution agent sensors. In the first case, the general concept of scale can be
     applied to both semantic and spatial scales, wherein the second case only applies to
     spatial scale.

10   <u>Cooperative Multiscale Perception</u>

     In this first case, a number of agents are specialized and adapted to analyze the image
     represented at certain scale levels, where for instance agents specialized for analyzing
     an image at level 'N' (58) cooperate with one another and further cooperate with
     agents specialized for a level 'N-1' (60). In this context, agents analyzing an image at
15   a scale level N can facilitate the analysis process by providing new information to
     agents at finer scale analyzing the base image data. As the agents at higher scale have
     a different and broader understanding on the nature of the object or region currently
     being analyzed, the provided information to the lower level agents will allow the latter
     to adapt their parameters and reorient their paths if required. The higher level agents
20   can also enforce restrictions on the lower level agents, where the agents can be bound
     to a specific region for instance. This multiscale cooperation can also comprise
     mutual feedback mechanisms where the knowledge and information gathered by
     agents at higher level can facilitate the lower level analysis, and where the lower level
     information can improve and facilitate the higher scale analysis. This coevolution
25   provides robust image analysis means as it simultaneously takes into account multiple
     scale representations of an image, allowing for increased robustness to noise and
     providing a global and local view of the information. Figure 7 depicts this concept of
     multiscale cooperation where agents on multiple scales cooperate with one another in
     order to efficiently analyze the raw image data. The herein described method of
30   cooperative multiscale perception and image analysis can further comprise the
     processes of agent reproduction and agent cloning where for instance when an agent
     that analyzes the raw image data finds itself in an uncertain environment or is unsure
     on the action it should perform due to the degenerated information, the agent has the
     possibility to clone or reproduce itself at higher scales, or inversely from higher scale
35   to lower scale. This requires the agent to first identify the scales at which it will
     instantiate new agents, then clone or reproduce itself to these scales, allow the new

5   agents to analyze the image they find themselves on, and update itself according to the information and knowledge provided by the new agents.

Multiscale Sensor Perception

In the case of sensor based multiscale perception, where only spatial scale is considered, the agents are composed of sensors adapted to provide a multiscale

10   representation of the portion of the image being sensed. The agent therefore has the possibility of considering the image at one spatial scale level or at a plurality of levels within the multiscale representation. Referring to Figure 8, this mechanism comprises the steps of first reading the data that is in range of the sensors by means of the sensors(62), following this, the data is then input to the Processor component which

15   computes a multiscale representation of the said data (64) using a method known in the art. The multiscale data representation can be input to the Neural Processor or further used by the Processor component. In one embodiment, the agent considers only one specific scale level of the multiscale image representation. In another embodiment, the agent sequentially or simultaneously considers a plurality of scale

20   levels. In yet another embodiment, the agent perceives the image at various spatial scales as well as in multiple resolutions, where the agent's sensors change in size to perceive a different level of information. This type of adaptation is useful when an agent is required to further validate the environment in which it is found so as to increase or decrease its confidence of the structure it analyzes. Referring to Figure 9.a,

25   the sensor data is input to either or both the Processor and the Neural Processor (66) where the data can be analyzed and processed, after which a response is sent to the Actuator that changes the size of the sensors (68) according to the later response. This process is repeated as required. This sensor adaptation is represented in Figure 9.b, where the initial sensor state is depicted by (70), and where after adaptation the

30   sensors are seen to be larger in size (72), meaning that more image data is being read by the sensors. In one embodiment, this type of adaptation is used to perceive a larger image region to ensure the agent is precisely detecting a contour.

Agent Negotiation

In order to resolve problems or contradictions as well as to facilitate the emergence of

35   optimal solutions in the image segmentation process, the present system provides a means for Agent Negotiation. In a preferred embodiment, the agent negotiation is

5   done by agents of different specialization that attempt to analyze the same image region. The objective is to allocate the image region to the agent that has maximum confidence on the segmented region. The process consists in first identifying the litigious region and for each agent to thereafter:

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- Evaluate considered region according to specialization;
- Communicate with other agents in litigious state;
- Vote for winning agent.

The first step of identifying the litigious region is achieved in one embodiment by a program that verifies if there is a plurality of agents that attempt to analyze a same image region. In another embodiment, an agent itself verifies if any other agents are analyzing the current region. In such case, the current agent evaluates the confidence that the said region is to be analyzed by itself. Following this evaluation, the agent communicates with the other agents in the litigious region and asks for their confidence value. The communicating agent can thereafter award the said region to the agent with maximum confidence. In one embodiment, the confidence value is computed by the agent's Processor. In another embodiment, the confidence value is attributed by a classifier such as a neural network using the agent's Neural Processor, where the neural network's activation value can be considered to weigh the confidence value.

Agent Adaptation, Collaboration and Reproduction

25   To provide increased robustness and intelligence to the system, the devised agents within the present multi-agent system have been incorporated means to dynamically adapt themselves to any image they analyze.

A first type of adaptation is the context based agent adaptation, where an agent adapts its parameters and goals based on the information the agent gathers at a higher semantic or spatial scale or based on the information provided by another agent found at a higher semantic or spatial scale. The agent first begins analyzing the image at its current scale level, then, to validate that the segmentation is precise and correct the agent gathers information from a higher scale which provides detail on the location and nature of the object being segmented. By having knowledge on the nature of the object, as provided from a higher scale analysis, the agent's behavior and actions can be dynamically modulated and adapted to improve the current segmentation, if

5   required. As stated above, the gathering of information at a higher level can be
achieved by the considered agent or by another agent at this higher level. In the
embodiment of gathering higher level information, the process involves the steps of:
1) Determining the scale level at which additional information should be gathered, 2)
Proper agent initialization, 3) Information gathering, and 4) Agent adaptation. In a

10   preferred embodiment, the adequate scale level is determined before-hand. The
second step of agent initialization can take many forms, such as, without limitation,
the agent moving itself to the higher scale, the agent cloning itself to the higher scale,
and instantiating new agents (can be of different specialization) at the higher scale by
reproduction or other means. In the first case where the agent at scale level i (74)

15   moves to the scale level n (76), the later analyzes the region of interest at the higher
scale to gain new knowledge on the feature or object being analyzed. Referring to
Figure 10.b, this process requires the agent to first identify the coordinate which it is
currently at within the image (78), then load the higher scale image representation
from memory (80), set it as the current image of interest (82), begin analyzing the

20   image at the previously identified coordinate (84), and finally update its memory and
adapt its parameters (86). In the other case, the agent clones itself at the higher level
and continues the analysis through direct collaboration with its higher level clone(s).
This is similar to the just above stated method, but differs with the aspect of
collaboration. Instead of a sequential process where the agent gathers information

25   then adapts itself, the cloning method provides a parallel and dynamic adaptation
method where the lower level agent dynamically adapts itself from the feedback
provided by its higher level clones. Referring to Figure 10.c, this method requires the
agent to first instantiate a new agent of same specialization (88), copy its mental state
and memory content to the new agent (90) so that the later becomes a clone (copy),

30   position the clone at the proper coordinate at higher scale (92), have the clone analyze
the image (94) and communicate the gathered information to the lower level agent
(96). In a preferred embodiment, an agent can simply invoke its "clone" class method
to clone itself, wherein the said class method is preprogrammed to generate a copy of
an instance of an agent. The other method provided for proper agent initialization is

35   the instantiation of new agents at the higher scale. As stated above, this can be
achieved by simple instantiation or reproduction. In such case, new agents of same or
different specialization will be instantiated and positioned at the proper coordinate on
the higher scale image by the lower level agent. These new agents will thereafter

5   analyze the image region and provide new information to the lower level agent by means of communication. The overall process is identical to the previously defined method, wherein the only difference lies in the type of agents that are instantiated. In the context of agent instantiation by means of reproduction, it is possible to instantiate new agents of specific specialization depending on the reproduction process of a

10   specific agent. In the present invention, agent reproduction can be general or specialized, where for instance in one embodiment an agent specialized to detect object contours has the possibility of reproducing itself in agents specialized in analyzing image background and object regions. By providing specialized reproduction schemes, agents have the possibility of collaborating and gaining new

15   knowledge optimally and specifically for the tasks they are required to do.

Another type of adaptation is based on reinforcement. The agent begins a first analysis, and then after a given number of pixels have been analyzed, the agent reiterates the analysis from the start. This reiteration allows for the agent to iteratively increase its knowledge on the information that is being analyzed and also offers the

20   possibility of exploring differing analysis methods. This method allows an agent to incrementally update its knowledge and understanding of the object or feature it is currently analyzing and can therefore optimally adapt its analysis parameters in accordance to its current knowledge. The adaptation involved can be with respect to the parameters relating to the Processor component or the Sensors, where for instance

25   the agent can modulate its noise sensitivity, adjust its threshold parameters, and vary the scale and resolution of its sensors.

Detailed description of the Invention in the preferred embodiment of Satellite Image Analysis

A detailed description of the present invention will be further described hereunder

30   using the example of detecting entities such as industrial buildings and bridges in satellite images, as well as further providing a symbolic interpretation of the image landscape.

Firstly, the system reads a digital satellite image by means of its input device, as depicted by numeral 2 in Figure 1. An illustration of a satellite image is depicted by

35   Figure 11, which contains bridges, buildings, roads and water courses. Then, the Program (4) preprocesses the digital image with objective of extracting the

5   . predominant water structures within the image which will thereafter serve as the
    initialization point for the multi-agent system. A possible method for extracting the
    main structures is to simply smooth the image at a high level by convolution with a
    Gaussian kernel followed by a threshold of pixels so as to only keep the pixels that are
    part of main water structures. Then the ridges of these main structures are extracted
10 by means of a ridge extraction operator. Figure 12.a depicts the extraction of the most
    predominant water courses along with their ridges. Referring to Figure 12.b,
    following these preprocessing operations, the Program instantiates three agents
    specialized for the following of ridges, in accordance to the three ridge entrance
    points (98,100,102). The Program extracts the coordinates of these entrance points
15 and assigns the agents respectively at these coordinates within the image. The
    objective of the ridge agents is to follow the ridge that serves as a path and thereafter
    collaborate with other agents if required. Once these agents have been initialized and
    assigned, the multi-agent system becomes autonomous. In the next step, the ridge
    agents initialize border agents that will analyze the border of the water structures. The
20 border agents are not directly guided by a path but instead use their sensors to orient
    their selves in the proper direction. The border agents are specialized to respond to
    bimodal input from their sensors as they are expected to perceive pixel values within a
    specific range on one side and pixel values with a different intensity range on the
    other side. This is from the fact that pixels that are part of the water structures will
25 have a different intensity then the land or other non-water structures in the image.
    Based on this *a priori* knowledge, the border agent will be able to recognize water
    borders and move within the image in accordance, while at the same time segmenting
    the borders for thereafter allowing further analysis.

    The next step consists in the agents to move within the image and analyze its content.
30 Referring to Figure 13, during the ridge path following, the ridge agents will
    encounter a forking in the path (104,106,108). When a ridge agent identifies the
    problem, it generates offspring of same type in a number according to the number of
    branching paths. These offspring will continue to follow ridges in an autonomous
    manner. At the same time, border agents analyze the image using their sensors and
35 move along the water course borders. Referring to figures 14.a and 14.b, the border
    agents will encounter a bridge (112) in their path which will be seen by the agent as a
    path discontinuity since the bridge line traverses the water and part of the bordering

5   land (114). This discontinuity will be identified by the concerned agent (110) and will trigger that adaptation of the agent's sensors to verify the nature of this discontinuity. The agent's sensors will successively increase in size and scale representation until the border edge on the other side of the yet unknown discontinuity (116) is sensed by the agent. At this point, the agent reproduces itself in a new Line Agent that is

10   initialized on the line discontinuity. The objective is to allow this new agent to gather more information on the latter. At this point, the Border agent has identified a discontinuity that crosses the border which provides an insight on the nature of the latter: can possibly be a building, a port, a road or a bridge. The new line agent will provide the border agent with enough information to make the proper identification of

15   the structure.   Now that the line agent is initialized it begins the analysis and following of the line structure. This specific agent performs basic edge enhancement to compute the necessary information to move in the proper path direction and simultaneously analyses the pixel values on both sides of the line (118). By detecting and analyzing these pixels, the agent can verify whether the pixels correspond to

20   water or land. Since in the present case the pixels along the path correspond to water, the line agent communicates with the Border agent and informs it that the discontinuity structure corresponds to the entity "bridge". The line agent continues its path until it reaches the end of the line, where if it encounters another border agent (120), it can also inform it on the nature of the current line structure.

25   The next process in the analysis consists in providing a symbolic and semantic interpretation of the water courses. In such case, the agents are required to collaborate at various spatial scales in order to properly detect and understand the present structures, without being disrupted by noise, artifacts, or other dominant structures. Relating to Figure 15, we can notice the presence of primary (122) and secondary

30   (124) water courses that are to be detected, segmented and interpreted by the system. First, in continuation with the previous processes, we see that the ridge agents come to a point where their paths meet (126-128, 130-132). This contradiction triggers negotiation amongst the considered agents. In this case, as the agents correctly follow the same path, the negotiation will result in a fusion of both considered agents (126

35   and 128, 130 and 132). Referring to Figure 15.b, the resulting fused agents (134, 136) will contain the knowledge acquired throughout the analysis of both agents, which means that the agent will have in memory the path of the complete water course ridge.

5   This fusion results in the generation of the symbolic concept of "same" meaning that
       this path consists of a single water course. Now that there remains two fused ridge
       agents, another level of interpretation can be provided. Both agents (134 and 136)
       have the knowledge that there initially was a split in path and that the result was a
       fusion of agents since they were on a same path. From this information, the agents'
10   State Machines will provide the conclusion that both agents may be part of a same
       water course, and that the separation may be caused by an entity such as an Isle,
       platform, or ship, for instance. To validate this, both agents instantiate an agent
       specialized in detecting blob structures at high spatial scales. Referring to Figure 16a,
       this is achieved through collaboration by first selecting a high spatial scale
15   representation of the current image and instantiating both new agents (138, 140) at the
       coordinates of their respective "parents" in the new image. Their goal is to detect a
       blob structure (142) in the vicinity of their initial coordinates. The two lower-scale
       parent agents restrict the possible displacements of the higher-scale agents by
       confining them within the range of both agents (144), based on their knowledge that
20   the structure is between them. Once initialized, the agents go about analyzing the
       region to detect and segment the "blob" structure. Further in the process, both blob
       agents will try to segment the same pixels, which indicates that they are detecting the
       same structure. From this, the lower-scale agents will be provided with the knowledge
       that this is in fact the same water course containing an entity. At this step, the system
25   may chose to continue the blob detection in order to provide symbolic and semantic
       interpretation of this entity. In the present case, based on the shape and spectral
       intensity of the entity, the agents can conclude that it consists in an Isle or sand bank.
       In another scenario, this entity could be a ship, where in such case, the blob agent
       would detect that it is a ship based on the entity's specific shape by means of its state
30   machine and memory unit. To achieve this identification, the agents are first required
       to precisely segment the structure and extract shape descriptors, such as maximum
       and minimum diameters, as well as spectral descriptors. By inputting this information
       in both or either their Neural Processor and State Machine, the agents will have the
       possibility of precisely identifying the analyzed structure and assign it a symbolic
35   value, as mentioned previously.

       Throughout these processes the border agents go upon segmenting the water borders.
       Now that the ridge agents have identified a single water course, the border agents

5   collaborate with the later to segment the whole water course. The objective is to relate

both borders to the appropriate water course, to quantify and analyze the water course

and to thereafter identify connecting courses. Quantifying and analyzing the water

course requires the agents to simultaneously perform the analysis at multiple spatial

scales so as to gather the most precise and robust information, allowing for further

10   detecting structures within and on the periphery of the water course. First, one of the

remaining ridge agents positions itself at the beginning of the ridge path and displaces

itself at the same coordinate in a higher spatial scale representation. Its objective is to

inform the agents to which ridge and water course they belong to and to instantiate

Water Agents that will analyze the water course. From its higher scale perception of

15   the structures, the ridge agent readily sees that the border agents directly belong to the

same water course. As the ridge agent moves along the ridge path it instantiates water

agents. These new agents are specialized to analyze water structures by means of their

multiscale sensors. These agents' sensors simultaneously perceive the locally sensed

pixels at multiple spatial scales. This multiscale view generates a multiscale

20   "signature" that is directly analyzed by their Processor and Neural Processor

components. The Neural Processor will classify the signatures according to these two

classes: water and non-water. This simple binary classification allows the agent to

take the appropriate actions upon the classification output. If the Neural Processor

identifies a signature as non-water, then the agent may be in the presence of an entity

25   such as a ship. In a specific embodiment, the water agent can reproduce itself in

agents specialized to segment such entities. The water agents are constrained by the

borders previously segmented by the border agents, which prevents them from

segmenting and analyzing structures that may have similar signatures as water pixels.

Furthermore, since the water agents sense the image at multiple scales, they are robust

30   to noise present within the image. At the end of the process, the water agents will

have segmented the complete water course and other entities will have been further

segmented and analyzed by other agents. The collaboration of border agents and

water agents also further allows for the segmentation and identification of bordering

structures such as buildings. In this case, the buildings will be seen as small

35   discontinuities by the border agents, while at the same time perceived as non-water

entities by the water agents. The water agents can therefore instantiate other

specialized agents to segment and analyze these bordering entities. At the same time,

the border agents can constrain the analysis domain of these new agents.

5   Overall, by letting evolve the previously described processes, the entire image and
       image structures will be precisely segmented, quantified and characterized. The
       agents will go upon achieving their goals and the overall autonomous collaboration
       will result in the complete quantification and understanding of the therein contained
       structures. The final step of the overall process consists in storing the segmented
10   image as well as the symbolic interpretation of every identified structure in a
       repository such as a database. The assignment program can execute this task by
       accessing the information contained in memory and appropriately storing it in a
       database. This stored information can be used by other programs, such as data-mining
       programs and display program, and can be directly interpreted by users.

15   While the invention has been described in connection with specific embodiments
       thereof, it will be understood that it is capable of further modifications and this
       application is intended to cover any variations, uses, or adaptations of the invention
       following, in general, the principles of the invention and including such departures
       from the present disclosure as come within known or customary practice within the
20   art to which the invention pertains and as may be applied to the essential features
       hereinbefore set forth, and as follows in the scope of the appended claims.